Supporting Information for "Northern Hemisphere monsoon response to mid-Holocene orbital forcing and greenhouse gas-induced global warming"

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Contents

Introduction

Here, we provide additional figures and tables to support our results.

Table S1 lists the model subset used in this study and extracted from PMIP3 - CMIP5 archive. The table also lists model resolution (spectral, if applicable) and the land component if available. The model subset includes only available models for both the mid-Holocene and the Representative Concentration Pathway 8.5 (rcp8.5) experiments, in order to avoid differences arising from different choices in the model physics.

Table S2 lists global mean temperature (T_{mean}) and inter-hemispheric thermal contrast (ΔT_{hem}) between the NH and the SH, calculated for each model and for the ensemble mean (Ens.), the three considered experiments.

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Section 1 describes the moisture budget decomposition used to interpret the different monsoon response in the two experiments and section 2 briefly describes the main features of figures S3, S4.

1 Moisture budget decomposition

The moisture budget equation is:

$$\rho_w g(P-E) = -\int_{p_t}^{p_s} (\overline{\mathbf{u}} \cdot \nabla \overline{q} \; + \; \overline{q} \nabla \cdot \overline{\mathbf{u}}) \; dp \; - Res \tag{1}$$

where Res is the residual composed as:

$$Res = \int_{p_t}^{p_s} \nabla \cdot (\overline{\mathbf{u}' q'}) \; dp \quad + S \tag{2}$$

Here overbars indicate monthly means and primes indicate departure from the monthly mean, p is pressure, q is specific humidity, $\overline{\mathbf{u}}$ is the horizontal vector wind, ρ_w is the water density and S is surface quantity. All integrals are computed between top and surface (respectively p_t and p_s) pressure levels on which every model has been vertically interpolated (1000, 925, 850, 700, 600, 500, 400, 300, 250, 200, 150, 100, 70, 50, 30, 20, 10 hPa). Following Trenberth and Guillemot (1995) and Seager, Naik, and Vecchi (2010) the anomalous moisture budget can be decomposed as:

$$\begin{aligned}\rho_w g \delta(P-E) \;=\; & -\int_{p_t}^{p_s} (\overline{\mathbf{u}}_{\mathrm{piControl}} \cdot \nabla \delta \overline{q} \; + \; \delta \overline{q} \nabla \cdot \overline{\mathbf{u}}_{\mathrm{piControl}}) \; dp \; + \\ & -\int_{p_t}^{p_s} (\delta \overline{\mathbf{u}} \cdot \nabla \overline{q}_{\mathrm{piControl}} \; + \; \overline{q}_{\mathrm{piControl}} \nabla \cdot \delta \overline{\mathbf{u}}) \; dp \; - \int_{p_t}^{p_s} \nabla \cdot \delta(\overline{\mathbf{u}' q'}) \; dp \; - \; \delta S\end{aligned} \tag{3}$$

where every δ describes the difference between each experiment (mid-Holocene or rcp8.5) and the reference climate (piControl):

$$\delta(\cdot) \; = \; (\cdot)_{\mathrm{mid-Holocene\ or\ rcp8.5}} \; - \; (\cdot)_{\mathrm{piControl}} \tag{4}$$

and we have neglected quadratic terms. The lowest level has been replaced by surface pressure. The first integral on the right-hand side of Eq. (3) describes the change in specific humidity (decomposed into advective and divergent terms), while the the second integral describes the moisture flux convergence by the mean flow, decomposed into its advective and divergent terms as well. The third term describes contributions by the transient eddies (TE) and the last term involves surface quantities (S). Eq. 3 terms involving δq but no changes in $\overline{\mathbf{u}}$ are referred to as the thermodynamic contributors (TH) to $\delta(P-E)$ and terms involving $\delta \overline{\mathbf{u}}$ but no changes in q as dynamic contributors (DY).

Because only data at monthly resolution are available for all models, the δTE component cannot be computed explicitly. In fact only the IPSL-CM5A-LR distributed daily outputs for mid-Holocene, piControl and rcp8.5. Hence, in our collection of models δTE has been calculated as a residual:

$$\delta TE \; = \; \rho_w g \delta(P-E) \; - \; \delta TH \; - \; \delta DY \; - \; \delta S \tag{5}$$

where specifically:

$$\delta TH \;\; = \;\; -\frac{1}{\rho_w g} \int_{p_t}^{p_s} (\overline{\mathbf{u}}_{\mathrm{piControl}} \cdot \nabla \delta \overline{q} \; + \; \delta \overline{q} \nabla \cdot \overline{\mathbf{u}}_{\mathrm{piControl}}) \; dp \tag{6}$$

$$\delta DY \;=\; -\frac{1}{\rho_w g}\int_{p_t}^{p_s}(\delta\overline{\mathbf{u}}\cdot\nabla\overline{q}_{\mathrm{piControl}} \;+\; \overline{q}_{\mathrm{piControl}}\nabla\cdot\delta\overline{\mathbf{u}})\;dp \tag{7}$$

$$\delta S \;=\; -\frac{1}{\rho_w g}\nabla\cdot\delta\int_{p_t}^{p_s}(\overline{\mathbf{u}}\cdot\overline{q})\;dp - \delta TH - \delta DY \tag{8}$$

2 Moisture budget differences between the mid-Holocene and the rcp8.5

Figure S1 and S2 show precipitation and evaporation anomalies relative to piControl for the mid-Holocene and rcp8.5, respectively.

Figure S3 and S4 show each component of the moisture budget for mid-Holocene and rcp8.5, respectively.

Table S1. PMIP3 model list for mid-Holocene, the piControl and future climate scenario rcp8.5 from r1i1p1 ensemble. Resolutions are indicated in terms of spectral resolution (when available), number of horizontal gridboxes and number of vertical levels.

	Models	Horizontal and vertical resolution	Land model
1	bcc-csm1-1	$T42\times 26$ $[128\times 26]$	BCC-AVIM1.0
2	CCSM4	$288\times 192\times 27$	CLM
3	CNRM-CM5	$TL127$ $[256\times 126]$	ISPA
4	CSIRO-Mk3-6-0	$T63\times 35$ $[192\times 96]$	-
5	FGOALS-g2	$128\times 60\times 26$	CLM3
6	HadGEM-ES	$192\times 72\times 38$	TRIFFID
7	IPSL-CM5A-LR	$96\times 95\times 39$	ORCHIDEE
8	MIROC-ESM	$T42\times 80$ $[128\times 64]$	MATSIRO
9	MRI-CGCM3	$T159\times 48$ $[320\times 160]$	-

References

Seager, R., Naik, N., & Vecchi, G. A. (2010). Thermodynamic and dynamic mechanisms for large-scale changes in the hydrological cycle in response to global warming. *Journal of Climate*, *23*(17), 4651–4668.

Trenberth, K. E., & Guillemot, C. J. (1995). Evaluation of the global atmospheric moisture budget as seen from analyses. *Journal of Climate*, *8*(9), 2255–2272.

Table S2. Global mean surface temperature (T_{mean}) and inter-hemispheric thermal contrast between the Northern and Southern Hemisphere (ΔT_{hem}) in JJAS for piControl, mid-Holocene and rcp8.5 for each model listed in Table S1. Last row shows values for the multimodel ensemble mean.

	T_{mean} [K]			ΔT_{hem} [K]		
	piControl	**mid-Holocene**	**rcp8.5**	**piControl**	**mid-Holocene**	**rcp8.5**
bcc-csm-1-1	288.1	288.2	291.1	8.2	8.8	8.8
CCSM4	288.1	288.1	292.3	9.8	10.2	10.0
CNRM-CM5	288.0	288.5	291.9	9.2	9.5	9.4
CSIRO-Mk3-6-0	287.5	287.8	291.5	9.9	10.3	10.5
FGOALS-g2	287.3	286.8	290.3	8.9	9.6	9.8
HadGEM2-ES	288.6	289.2	293.0	8.8	9.5	10.3
IPSL-CM5A-LR	287.0	287.2	292.2	9.1	9.8	10.8
MIROC-ESM	287.7	288.1	292.6	10.5	10.5	11.7
MRI-CGCM3	288.4	287.7	291.6	8.2	8.8	8.9
Ens.	287.8	288.1	292.0	9.2	9.7	10.0

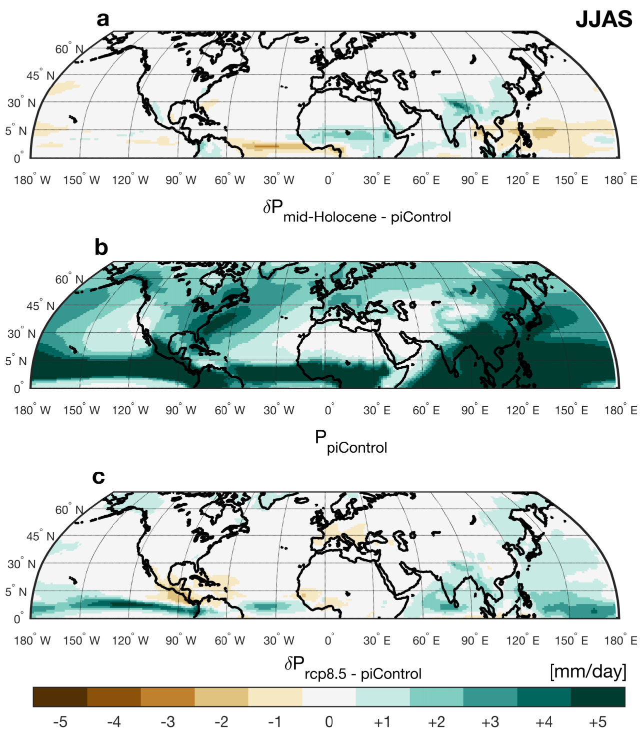

Figure S1. Precipitation anomalies (mm/day) defined as the difference between mid-Holocene (a) and rcp8.5 (c) and the piControl (b) ensemble means.

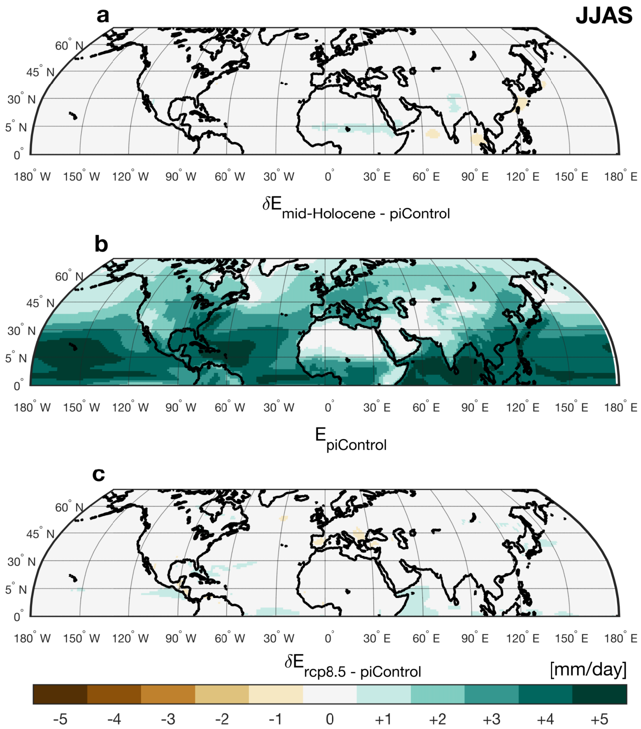

Figure S2. Evaporation anomalies (mm/day) defined as the difference between mid-Holocene (a) and rcp8.5 (c) and the piControl (b) ensemble means.

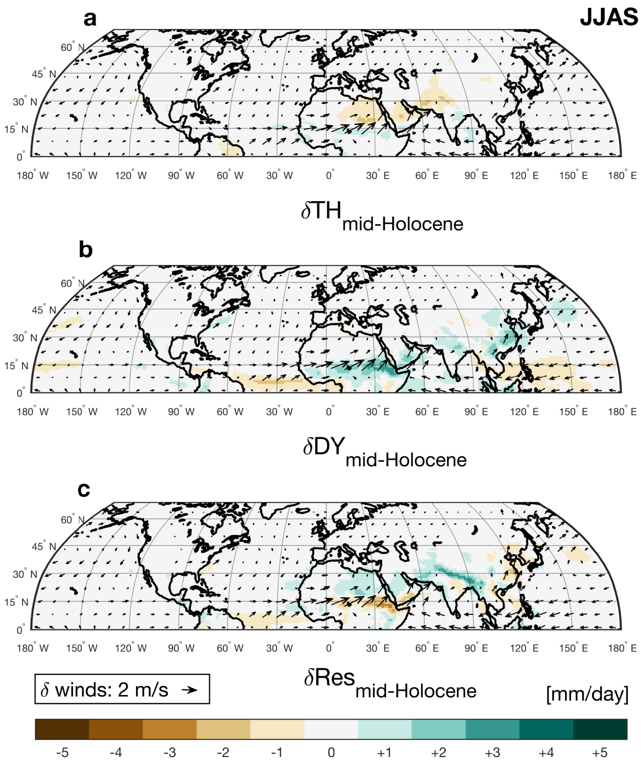

Figure S3. Shading shows the thermodynamic (δTH), dynamic (δDY) and residual (δRes) contributions to the anomalous JJAS moisture budget in mid-Holocene relative to piControl. Arrows indicate 925-hPa wind change in mid-Holocene relative to piControl.

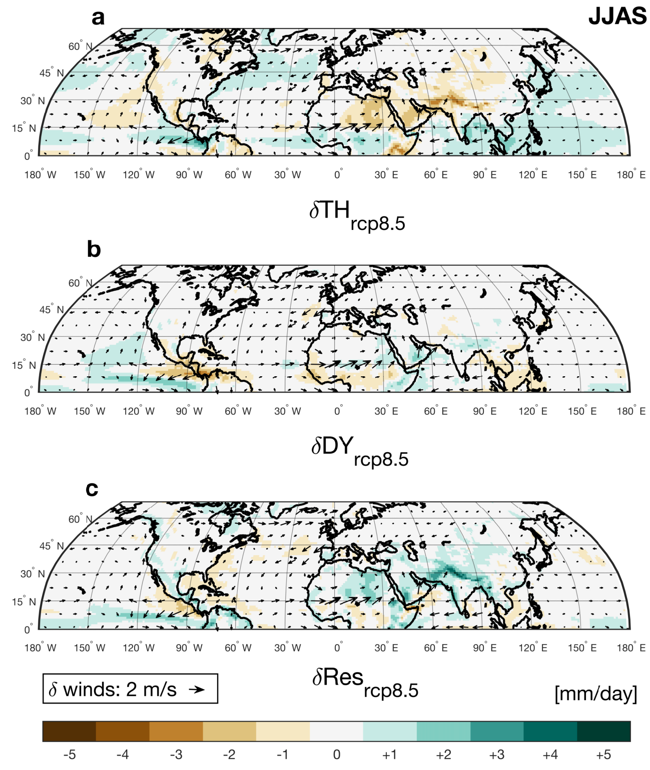

Figure S4. Shading shows the thermodynamic (δTH), dynamic (δDY) and residual (δRes) contributions to the anomalous JJAS moisture budget in rcp8.5 relative to piControl. Arrows indicate 925-hPa wind change in rcp8.5 relative to piControl.

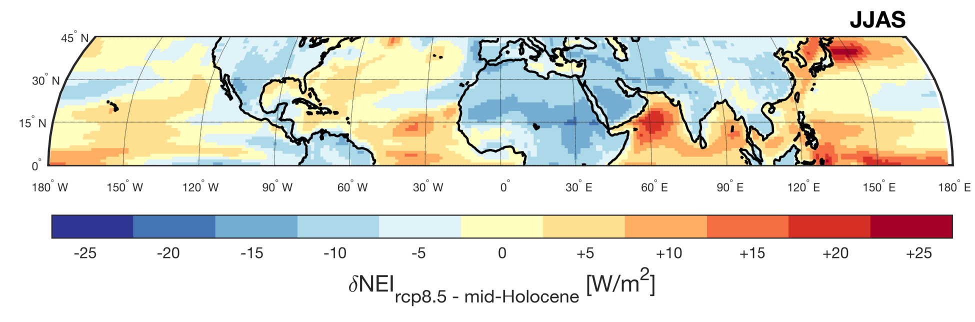

Figure S5. Net energy input (NEI) difference between rcp8.5 and mid-Holocene in June-to-September (JJAS) ensemble means (shading).